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Analysis of Aerodynamic Load Effect on Thin Plat Section in Multiple Fan Active Control Wind Tunnel

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Abstract

In atmospheric boundary, the power spectral density of turbulent wind simulated passively by the grid layer is regulated difficultly with the problem of smaller integral length of turbulence. For the advantage of active control method in adjusting the power spectral density and the integral length more simply, 11×9 multiple fan active control wind tunnel in Miyazaki University is utilized to debug many kinds of harmonic turbulent wind. Three-component aerodynamic forces on thin plat section (aspect ratio 22.5:1) in the harmonic turbulent wind field were measured by using the high frequency force balance of better stability and precision with testing the turbulent wind synchronously. The load effects on the model under different conditions, such as mean wind velocity, fluctuation frequency, turbulence intensity and integral length, were compared and analyzed. Frequency doubling amplification effect caused by the fixed wall boundary reflection effect in atmospheric boundary physical wind tunnel was reported and confirmed. In the validated effective frequency range where discrete frequency load effect caused by sinusoidal turbulent wind can be linearly superposed, the impacts on aerodynamic load effect induced by turbulence integral length and turbulence intensity were analyzed preliminarily. The differences between the conventional buffeting force theory and the wind tunnel test results of typical section model were clarified.

Keywords: Multiple fan active control, sinusoidal turbulent wind, thin plate section, aerodynamic load.

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1. INTRODUCTION

To the main span of cable-stayed bridge over 800m and suspension bridge over 1500m, identification theory and technology of the relevant parameters (such as static wind coefficient, flutter derivatives and aerodynamic admittance) for the aerodynamic loads in wind tunnel test based on precise methodology has become the key technology in wind-resistance design. It is noted that the random buffeting theory having close ties with the conversion between time domain and frequency domain for the aerodynamic effects and spatial correlation has not yet broken through the theoretical framework of streamlined section. Especially the study for the turbulence integral scale effect and non-linear load effect of incoming flow turbulence is basically blank.

In aerodynamic admittance function used for quasi-steady correction in description of aerodynamic load on bridge section, the upper and lower limit are taken as 1 and sear function of thin plate section in engineering applications separately. The calculation results based on the two values can lead to double error. A number of similar assumptions are introduced in the recognition algorithm of aerodynamic admittance, and flow conditions such as the integral scale can not be controlled precisely, so it is difficult to reproduce the classical analytical result of Sears function for rigid airfoil and verify the validity and rationality of the results (Qin and Gu 2004; Zhao and Ge 2010; Zhou 2009; Li 2007).

In response to these points, it starts by improving simulation conditions of flow in the physical atmospheric boundary layer wind tunnel. The aerodynamic loads variation law on thin plate section in different frequency and wavelength condition of sinusoidal flow is discussed by using multiple fan active control wind tunnel in Miyazaki University of Japan.

2. EXPERIMENTAL ARRANGEMENT

2.1. Wind tunnel conditions and facilities

Fig.1 shows active wind tunnel of Miyazaki University composed of 99 (11×9) independent blowers and the installation of model in wind tunnel.

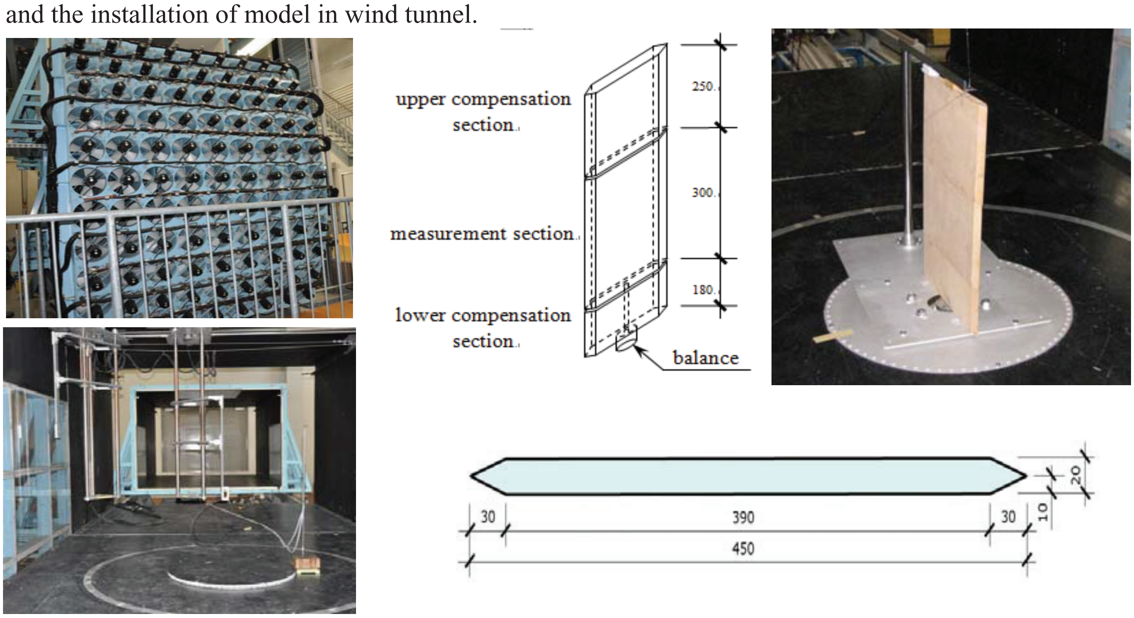


Figure 1: Schematic of multiple-fan wind tunnel and installation of the model

It can effectively simulate the average wind and turbulence profiles and reasonably represent wind-time history of sine wave and broadband turbulent wind with different integral scale (Nishi et al. 1997; Nishi et al.1999; Cao et al. 2002; Pan et al. 2010). The test section dimension is 2.538m wide and 1.804m high. Wind velocity ranges from 0 to 15m/s adjustable continuously. High-precision three-component force balance is used to test section model aerodynamic load. Balance ranges is ± 20N (F_x, F_y) and ± 2N•m (M_z) with measure accuracy 1‰. Synchronous acquisition equipment is adopted to measure the turbulent wind and aerodynamic load at the same time. The measured frequency of the whole system after installation is 24Hz in the weak-axis direction and 44Hz in the strong-axis direction. So the system natural frequency is much larger than the dominant frequency of sinusoidal flow.

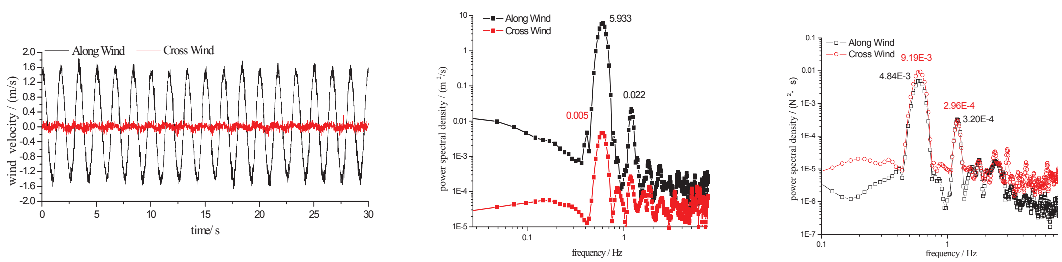
Table 1 shows the sinusoidal flow characteristics in experimental conditions.

Table 1: Characteristics properties of sinusoidal flow

	unit	value
Mean wind velocity：U	m/s	2, 4, 6, 8, 10, 12 m/s
Sinusoidal oscillation frequency : f	Hz	0.2, 0.4, 0.6, 0.8, 1.0, 1.2,1.6, 2.0, 2.5, 3.0, 4.0 Hz
Amplitude of velocity oscillation: A	m/s	0.06 ~ 2.41 m/s
Turbulence intensity: I_u	%	1.13 ~ 25.18%
Turbulence intensity: I_w	%	0.28 ~ 0.90%
Integral scales of turbulence of u: L_u^x	m	0.47 ~ 59.58 m
Integral scales of turbulence of w: L_w^x	m	0.01 ~ 2.32 m

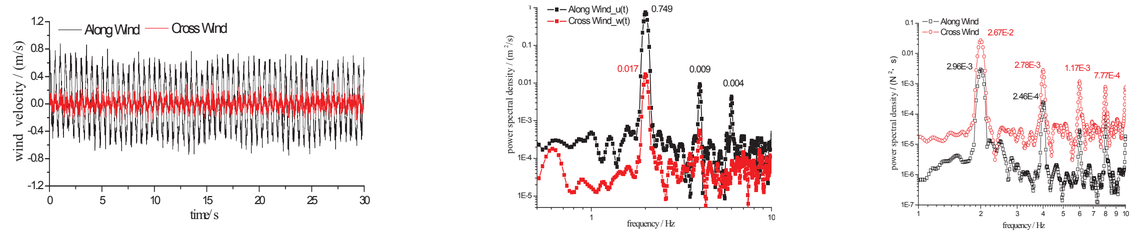
2.2. Sinusoidal flow simulation

Figure 2 shows the time history of low-frequency sinusoidal flow and corresponding spectral of turbulent wind and aerodynamic load on model. Compared to the cross-wind turbulence u, the along-wind turbulence w has an absolute advantage with the energy ratio of about 1200:1. Aerodynamic load spectral in along and cross-wind direction has a single dominant frequency respectively. Figure 3 shows the time history of high-frequency sinusoidal flow and corresponding spectral. Single high dominant frequency in sinusoidal flow causes the peak value of spectral in along and cross-wind direction at the frequency multiplication point.



(a) wind velocity time history (b) turbulent wind spectral (c) aerodynamic load spectral

Figure 2: Low-frequency sinusoidal flow and aerodynamic load effect (U=6.38m/s, A=1.19m/s, f=0.60Hz, L_u^x=10.13m,L_w^x=0.38 m, I_u=13.24%, I_w=0.51%)



(a) wind velocity time history (b) turbulent wind spectral (c) aerodynamic load spectral

Figure 3: High-frequency sinusoidal flow and aerodynamic load effect (U=6.43m/s、A=0.43m/s、f=2.00Hz、L_u^x=3.05m、L_w^x=1.44m、I_u=4.74%、I_w=0.78%)

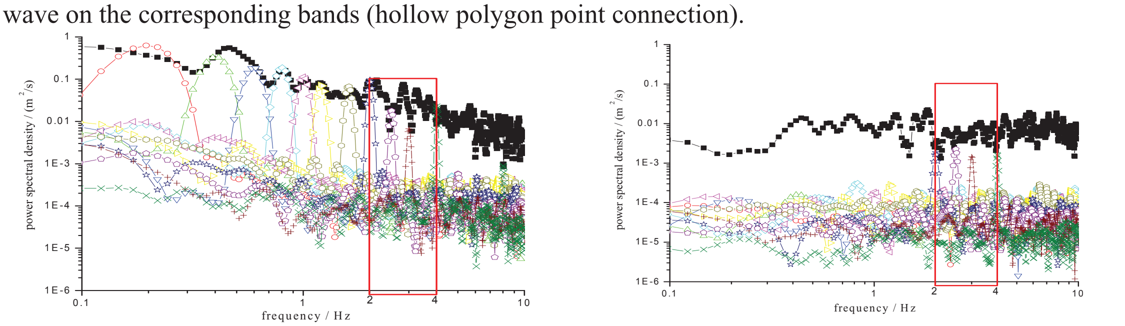
2.3. Numerical simulation of frequency doubling effects

In the process of analyzing load effects of sinusoidal flow on the bridge section by CFD (Cao 2008), it finds the frequency multiplication phenomena. It considers that this effect is caused by reflection resonance effect when the sinusoidal flow passes to the fixed numerical boundary wall. The similar effects also appear in this experiment. It follows that similar effects occurs in physical atmospheric boundary layer wind tunnel inevitably. The aerodynamic load in this band becomes large.

3. RESULTS

3.1. Linear superposition of discrete frequency

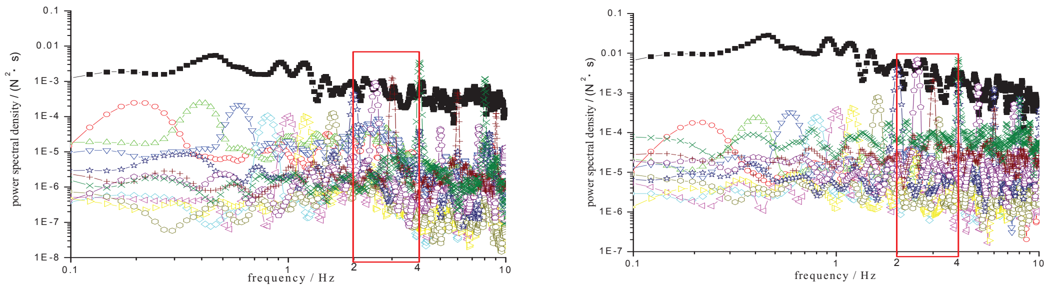
Because of frequency multiplication in the high frequency band, linear superposition effect of aerodynamic load does not exist. In order to further analysis the aerodynamic effect from single-frequency fluctuation to the broadband tuburlent wind, it needs to identify the range where linear superposition principle exists. In Figure 4, for multi-fan tuburlent wind simulation of broadband (solid rectangle point connections), it can compose of a series of different frequency and amplitude of the sine wave on the corresponding bands (hollow polygon point connection).



a) along-wind spectral of sinusoidal and broadband turbulence b) cross-wind spectral of sinusoidal and broadband turbulence

Figure 4: Discrete frequency linear superposition analysis for turbulence wind

In the range of 2.0-4.0Hz, if input energy of sinusoidal turbulent wind (including the u and w wind spectrum) is more consistent with that in broadband, the along-wind and cross-wind aerodynamic loads caused by single frequency fluctuation have higher agreement with that by the broadband turbulence (Figure 5). It suggests that the linear superposition principle lies in frequency from 2.0-4.0Hz. Besides, in order to obtain the aerodynamic load effect consistent with the real situation, it is necessary to improve the simulation of fluctuation wind in w direction in active wind tunnel.



(a) along-wind load spectral in sinusoidal and broadband turbulence (b) cross-wind load spectral in sinusoidal and broadband turbulence

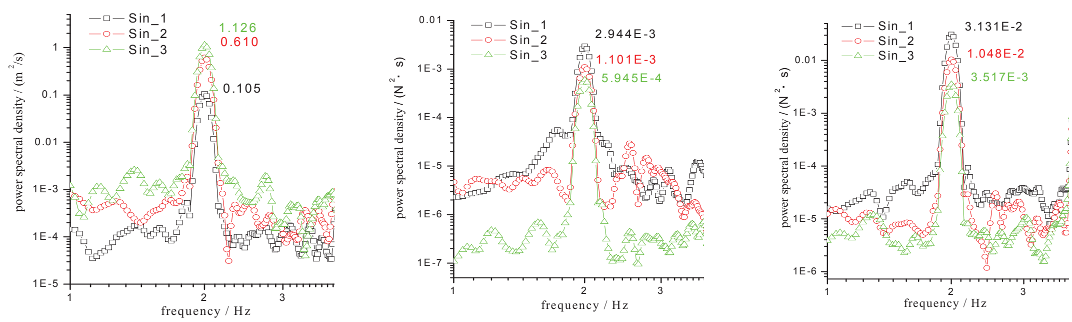
Figure 5: Discrete frequency linear superposition analysis for aerodynamic load

3.2. Integral scale effect

Turbulence integral scale is important in the wind load analysis of the structure. The size of integral scale determines the scope of wind effects on structures. It is generally considered that the integral scale is larger; the effect of the aerodynamic loads on the structure is more obvious. For this problem, it can make the following analysis. Three different wind velocity and amplitude of sinusoidal flow conditions are compared in Table 2.

Table 2 Parameters with different integral scale

	Mean wind velocity	Frequency	Amplitude	Turbulence intensity	Integral scale L_u^x
Sin_1	4.09 m/s	2.00 Hz	0.20 m	3.48%	1.78 m
Sin_2	8.35 m/s	2.00 Hz	0.39 m	3.29%	3.88 m
Sin_3	12.42 m/s	2.00 Hz	0.53 m	3.01%	5.81 m



a) along-wind spectral of sinusoidal turbulence b) along-wind load spectral c) cross-wind load spectral

Peak ratio: $W_3 / W_2 / W_1 = 10.72 / 5.81 / 1.00$ Peak ratio: $D_3 / D_2 / D_1 = 0.20 / 0.37 / 1.00$ Peak ratio: $L_3 / L_2 / L_1 = 0.11 / 0.33 / 1.00$

Figure 6: Comparison of integral length effect on aerodynamic force

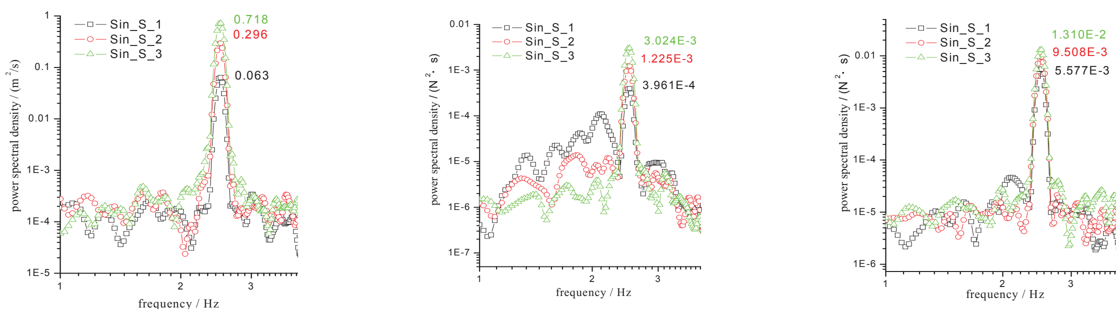
The three cases have the same single frequency and similar turbulence intensity. In traditional reorganization, it can consider preliminarily that in the smallest integral scale of case Sin_1 with the smallest energy amplitude of the sine wave, the aerodynamic load on model should be minimal and load effect in case Sin_2 and Sin_3 increase gradually. Compared with the test results in active wind tunnel (Figure 6), it gets the opposite conclusion. To a certain extent, it shows that the traditional theory is imperfect and true aerodynamic load law is complex.

3.3. Turbulence intensity effect

There are two kinds of case. One is the condition with small turbulence intensity (Iu≤5.0%), the other is that with large turbulence intensity (5.0%≤Iu≤30.0%). Other parameters are similar except fluctuation amplitude of wind speed and turbulence intensity. In these two cases, along-wind and cross-wind aerodynamic loads grow significantly with the increasing turbulence intensity (Figure 7 and Figure 8). Peak energy ration of along-wind force does not change significantly in large and small intensity case. But the absolute value of turbulence intensity exerts greater impact on change proportion of peak energy ration of cross-wind force. It appears that the load enlarging change rapidly with the increased turbulence intensity. For example, in small turbulence intensity, peak ration of cross-wind force spectrum is L3/L2/L1=2.35/1.70/1.00, but in large turbulence intensity, peak ration is L3/L2/L1=9.39/4.56/1.00 with the similar peak ration of turbulence spectrum. It reflects the secondary additional characteristics of load effects.

Table 3 Flow parameters with different turbulence intensity

	Mean wind velocity	Frequency	Amplitude	Turbulence intensity	Integral scale L_u^x
Sin_S_1	6.19	2.50 Hz	0.14 m	1.56 %	1.94 m
Sin_S_2	6.29	2.50 Hz	0.27 m	3.07 %	2.34 m
Sin_S_3	6.50	2.50 Hz	0.42 m	4.57 %	2.51 m
Sin_L_1	6.12	0.20 Hz	0.48 m	5.51 %	27.39 m
Sin_L_2	6.17	0.20 Hz	1.50 m	17.17 %	28.79 m
Sin_L_3	6.24	0.20 Hz	2.22 m	25.18 %	29.32 m

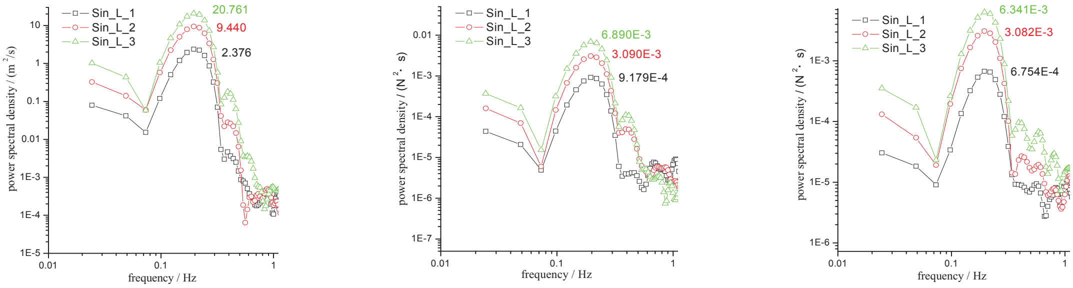


a) along-wind spectral of sinusoidal turbulence
Peak ratio: *W3 /W2 / W1* = 10.40 / 4.70 / 1.00

b) along-wind load spectral
Peak ratio: *D3 / D2 / D1* = 7.63 / 3.09 / 1.00

c) cross-wind load spectral
Peak ratio: *L3 / L2 / L1* = 2.35 / 1.70 / 1.00

Figure 7: Turbulence intensity impact on aerodynamic force under small intensity condition



a) along-wind spectral of sinusoidal turbulence
Peak ratio: $W3 / W2 / W1 = 8.74 / 3.97 / 1.00$

b) along-wind load spectral
Peak ratio: $D3 / D2 / D1 = 7.51 / 3.37 / 1.00$

c) cross-wind load spectral
Peak ratio: $L3 / L2 / L1 = 9.39 / 4.56 / 1.00$

Figure 8: Turbulence intensity impact on aerodynamic force under large intensity conditionn

4. CONCLUSION

Using active control method to divide broadband random turbulent wind into series of sinusoidal perturbation combination, the load effect mechanism on flat section is analyzed under different parameters in sinusoidal turbulent wind based on the principle that aerodynamic load effects in the verification band can make linear superposition. It shows that it is difficult for a simple random buffeting force theory to explain wind tunnel test phenomenon of the section model reasonably. It reveals the complexity of aerodynamic load effects on the typical two-dimensional structure. So in the subsequent study, it should expand the object from the flat sections to more blunt section.

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